A Low-Cost Wearable Exoskeleton for Sitting and Standing Assistance

Kayla Blalack[1,†], Leo Wang[1,†], Maximus Maldonado[1,†] Lauren Marbury[1,†], Soroush Zare[1] and Ye Sun[1,2,*]
[1]Department of Mechanical and Aerospace Engineering
[2]Department of Electrical and Computer Engineering, University of Virginia, Charlottesville, VA
{kab3u, lw9hm, mm5xaf, lam2tdh, cyj7tf, dzv7sg}@virginia.edu

2024 IEEE 20th International Conference on Body Sensor Networks (BSN) | 979-8-3315-3014-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/BSN63547.2024.10780629

***Abstract*—This paper presents the design, prototyping, and testing of a low-cost wearable exoskeleton that assists sitting-to-standing and standing-to-sitting (STS) transitions for users with lower limb mobility impairment. This exoskeleton design utilizes the mechanism of invisible chairs as the supporting structure and powers the knee and hip joints to provide fast and smooth transitions between sitting and standing. This exoskeleton features low cost, and minimally invasive design, making it suitable for everyday use. The study highlights the potential of this device to improve the quality of life for elderly individuals by promoting safer and more independent mobility.**

***Index Terms*—Lower-limb exoskeletons, assistive technology, sit-to-stand transition, elderly mobility, wearable robotics**

I. Introduction

As people age, their muscular strength and range of motion in the hips and knees decline, making activities like sitting and standing more difficult. This decline increases the risk of falls, which is one of the leading causes of aging population mobility impairments, with one in four older adults reporting falls yearly [1]. Sedentary lifestyles, often adopted due to these difficulties, can have detrimental health effects over time [2]. Although assistive technologies like exoskeletons can significantly enhance mobility and quality of life for the elderly [3], current designs are often expensive, bulky, and unsuitable for everyday use.

The growing elderly population necessitates new solutions to support their daily activities. There is a clear need for assistive devices that are affordable, lightweight, and non-intrusive to enable elderly individuals to maintain their independence and reduce the risk of injury [4]. A minimally invasive exoskeleton that assists with sit-to-stand transitions can significantly improve the quality of life by promoting safer and more independent mobility. Such a device would help physical rehabilitation and encourage a more active lifestyle, thereby addressing the adverse effects of sedentary behavior.

Existing exoskeletons for lower-limb function vary in material, actuation methods, and powered technologies. They range from soft to rigid materials [5], [6] and passive to active actuation [7], [8], utilizing electric motors [9], hydraulics [10], or pneumatics [11]. Most current designs are intended for rehabilitation and are not suitable for everyday use due to high costs and restricted mobility.

The proposed exoskeleton leverages the mechanism of invisible chairs for support and stability, significantly reducing overall cost and complexity. Our design enhances knee and hip joint functions while requiring minimal ankle mobility, allowing for seamless and natural movement. We utilized readily available materials to ensure the device remains lightweight and unobtrusive. The simplified actuation method, primarily driven by electric motors, eliminates the need for bulky and noisy systems, making the exoskeleton suitable for everyday use by individuals. This exoskeleton prototype promotes safer and more independent mobility. It aims to improve the quality of life for the elderly by encouraging an active lifestyle and reducing the risk of injury. By addressing the specific needs of the elderly population, our design provides a practical and effective solution to the challenges of aging, ensuring affordability, accessibility, and ease of use.

II. Exoskeleton Design

A. Human Body Modeling

Understanding the STS transition is crucial for designing a practical exoskeleton. The process of transitioning from siting to standing postures can be broken down into four distinct phases: flexion-momentum, lift-off, extension, and stabilization, as shown in Fig. 1. In the initial phase, known as flexion-momentum, the individual leans forward, shifting their center of gravity ahead of their base of support. This involves generating the momentum required to initiate the lift-off. During the lift-off phase, the individual begins to rise from the seat, characterized by the thighs lifting off the chair while the center of gravity continues to move forward. As the body begins its upward movement, the knees start to extend.

In the extension phase, the hips and knees move towards full extension, providing the necessary force to elevate the body to a standing position. The trunk continues to straighten, and the body moves upwards. The final phase is stabilization, where the individual reaches a fully upright standing position with hips and knees fully extended and the center of gravity aligned over the feet. At this stage, the body stabilizes, completing the transition from sitting to standing. These phases highlight the dynamic nature of the sit-to-stand transition and the importance of designing an exoskeleton that can effectively support and enhance each phase. The exoskeleton must provide the necessary support and assistance to the lower

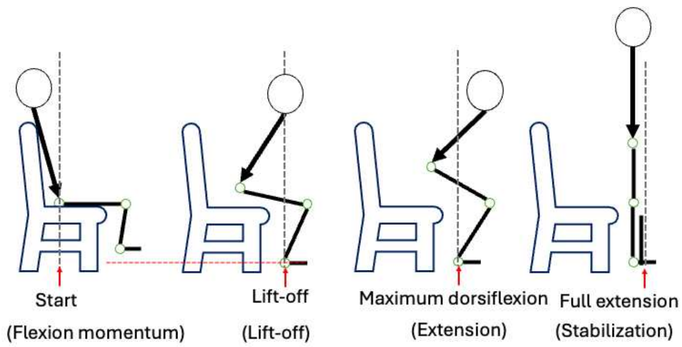

Fig. 1. The four phases of standing biomechanics.

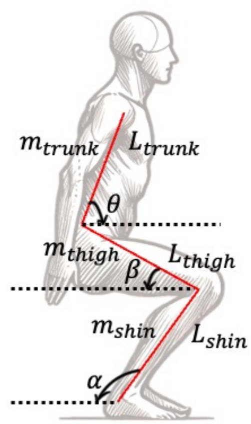

Fig. 2. The torque calculation diagram.

limbs during these critical moments to ensure a smooth and safe transition from sitting to standing. The biomechanical parameters of the sit-to-stand transition are illustrated in Fig. 2. The measurements obtained from our subjects are presented in Table I.

B. Design

The structural components of the prototype were meticulously designed using SolidWorks and subsequently 3D printed using ABS plastic, as illustrated in Fig. 3. While PLA offers greater stiffness, it is prone to cracking under applied stress, making it less suitable for this application. Conversely, ABS plastic, known for its toughness, was chosen for its ability to withstand higher tensile stresses. The parts were printed with sufficient thickness and high infill density to resist compressive forces effectively. The shafts that transferred motion from the motors to the full frame were also 3D printed in ABS plastic. These shafts are critical components that endure significant stresses. ABS plastic was chosen for these parts because it provides the necessary strength and durability, ensuring reliable performance in the final prototype. The design features a robust device that aids in standing and sitting. It utilizes a pre-existing mechanical system known as the "invisible chair," depicted in Fig. 3(a), which offers leg support to

TABLE I
TEST SUBJECT DIMENSIONS.

Link	Length (m)
Full Height (Standing)	1.829
Trunk (Hip to Neck)	0.549
Thigh (Hip to Knee)	0.483
Knee (Joint)	0.088

alleviate pressure on the lower limbs. This system is secured to the user with a workout belt around the hips, providing back support. Additionally, a tiny backpack houses the power source and control electronics. As illustrated in Fig. 3(c), our design incorporates four motors, with two on each leg—one positioned at the outside of the knee and the other at the outside of the hip. These components are mounted on 3D-printed frames that attach to the user's legs.

The exoskeleton assembly is detailed in Fig. 3(c). The blue elliptical shape represents the belt stabilizing the user's core, while the gray linkages connect the hip to the belt. The thigh linkage is composed of green and orange parts, segmented to fit within the constraints of the 3D printer. The cyan linkage connects the knee joint to the remainder of the leg. Pink blocks denote the NEMA 23 motors with integrated gearboxes, each driving a perpendicular shaft linked to the frame through 1:1 bevel gears, as shown in Fig. 3(d).

The invisible chair system includes velcro straps designed to thread through slots on the linkages, securing the frame. These straps are sufficiently robust to support the movement of the invisible chair and the exoskeleton. When tightened, the straps prevent any lateral movement of the exoskeleton, maintaining its correct position on the user's body. The velcro straps are wide, providing ample surface area to keep them securely fastened.

C. Control

The development of the control system involves several critical stages to ensure optimal functionality. With the control system, the mechanical design detailed in Section II.B was then powered and motorized as the lower-limb exoskeleton prototype to support an individual's weight and facilitate movement during sitting and standing. In this prototype design, human inputs were given through a button press, enhancing the system's portability and usability. Four selected stepper motors were configured to initiate practical motion control development as depicted in Fig. 4. This setup was successfully tested, running all four motors simultaneously at a constant velocity. The system operates with the AccelStepper Arduino library, facilitating smooth acceleration and deceleration of multiple motors during different motion stages. The toggle switch commands the system to sit or stand, while an emergency stop button halts all motion. The motors are powered by a portable power bank, enhancing system mobility. The battery's placement in an exterior pocket allows for modular replacement.

We conducted a video analysis of a test subject performing sit-to-stand movements to optimize motor operation range.

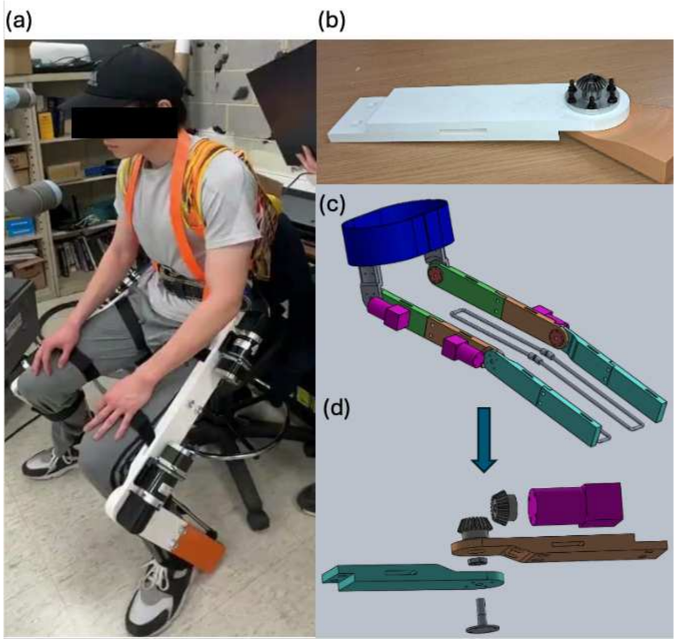

Fig. 3. The exoskeleton design for STS transition. (a) Exoskeleton worn by a user demonstrating its fit and support during a seated position. (b) The high infill plastic frame piece. (c) CAD model of the exoskeleton showing the integration of various parts. (d) Exploded view of the CAD joint model.

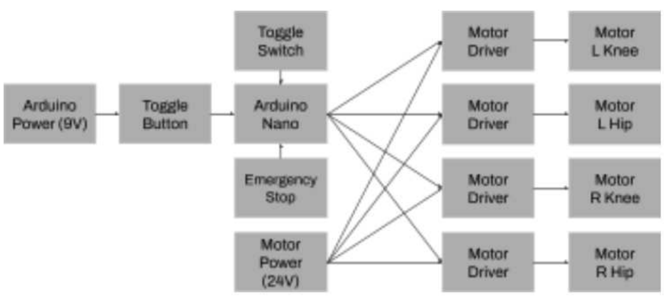

Fig. 4. Control and electronics overview.

The setup and motion tracking views are shown in Fig. 5. Five trials were conducted to ensure accurate calculations and reliable angular values. Table II shows the workspace of a designed exoskeleton. Table III presents the averaged quantitative results. Key observations include the two distinct phases of hip motion—linear and parabolic. During sit-to-stand transitions, hip movement precedes knee movement. The resulting angular position, velocity, and acceleration plots align with the smooth acceleration and deceleration.

Using more precise benchmarks from video analysis, each motor was assigned target positions, as shown in Table IV. The code runs simultaneous motor movements through three phases for both sitting and standing. However, system backlash has impacted the prototype's ability to achieve these benchmarks. A minor constant was introduced to the target positions to counteract this, ensuring the motors move slightly beyond the previously calculated positions.

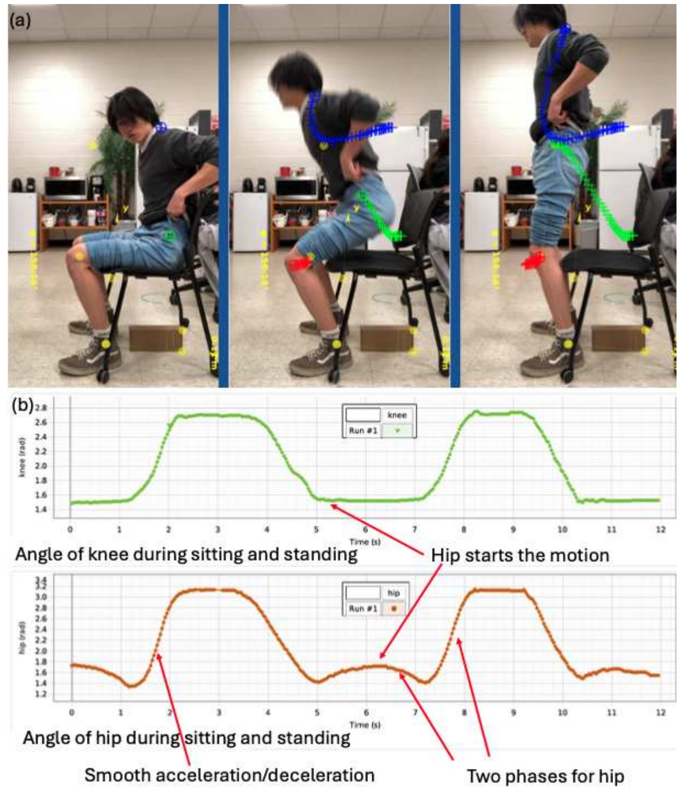

Fig. 5. Human joint analysis for control (a) Video analysis. (b) Knee and hip angles during sitting and standing.

TABLE II
DEGREES OF FREEDOM FOR KNEE AND HIP JOINTS DURING SITTING AND STANDING.

Joint	Sitting angle	Standing angle
Knee	60°	120°
Hip	50°	100°

TABLE III
SITTING AND STANDING JOINT MOTION.

Joint	Knee (rad)	Hip (rad)
Knee	-1.2	-1.68, 0.24
Hip	1.2	-0.35, 1.765

TABLE IV
TARGET POSITIONS FOR MOTORS.

	Phase 1	Phase 2	Phase 3
Hip Stand	3,015	3,765	0
Knee Stand	3,080	3,080	0
Hip Sit	0	3,542	3,015
Knee Sit	0	3,080	3,080

III. EXPERIMENTAL RESULTS

The final design, illustrated in Fig. 6, was assessed based on a predetermined set of specifications. The primary criteria for this final product included being minimally invasive, cost-effective, and weighing no more than 50 kg. The required forces to be resisted depend on the user's physical parameters. To ensure the device fully supports seated and standing

Fig. 6. Final exoskeleton design evaluation.

TABLE V
PERFORMANCE SPECIFICATIONS AND ACHIEVEMENTS OF THE EXOSKELETON PROTOTYPE.

Criterion	Benchmark	Achieved
Weight	50 kg/110 lb	Achieved, 37 kg/82 lb
Range of Motion	Knee 60° - 120°, Hip 50° - 100°	Achieved for Knee, Hip is missing 11°
Operating Time	5 - 10 s	Achieved, STS in 5 s
Reliability	Does not malfunction; always moves in the correct direction	Moves in the correct direction smoothly

positions, we utilized known sitting and standing angles to determine the necessary degree of knee and hip bending. Specifically, the knee must bend from a seated angle of 60° to a standing angle of 120°, and the hip from a seating angle of 50° to a standing angle of 100° [12]. These parameters are summarized in Table II. A successful exoskeleton must achieve this range of motion for the user.

To evaluate the usability and accuracy of our device, we conducted several continuous trials of sitting and standing with our test subjects. During these trials, we observed that the user could move slightly even when meant to be stationary, indicating some slack in the system. Despite this backlash, the desired motion was achieved efficiently, quietly, and safely. Table V provides our specifications, detailing the goals and outcomes for our final prototype.

IV. Discussion and Conclusion

This study develops a low-cost wearable exoskeleton that effectively assists with STS transitions, demonstrating its potential as a valuable tool for enhancing mobility. Key components of the design include the integration of a workout belt for hip support, a small backpack housing the power source and control electronics, and using 3D-printed frames to secure the motors and structural elements. The exoskeleton utilizes four motors strategically placed at the knee and hip joints to provide necessary movement assistance. The control system, currently operated via a button press, has proven reliable and user-friendly. Video analysis confirmed that the device achieves the desired range of motion for knee and hip joints, ensuring efficient and safe transitions between sitting and standing positions. The system operates quietly and efficiently, powered by a portable power bank that enhances its usability and convenience.

The exoskeleton also addresses vital specifications, such as weight, range of motion, operating time, cost, and reliability. The prototype successfully meets these benchmarks, weighing 37 kg, achieving the required range of motion for the knee, completing STS transitions within 5 seconds, and maintaining functionality under a cost-effective budget. The modular design allows for easy assembly and customization, making it accessible to various users. This exoskeleton represents an advancement in assistive exoskeleton technology, providing a compact, low-cost solution for the healthcare industry and elderly users. Its ability to enhance daily tasks and improve the quality of life for many individuals is notable. The simplicity of its parts facilitates easy manufacturing and potential mass production.

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